Paper

PAST AND PRESENT LEVELS OF SOME RADIONUCLIDES IN FISH FROM BIKINI AND ENEWETAK ATOLLS

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Abstract—**Bikini and Enewetak were the sites in the Northern Marshall Islands that were used by the United States as testing grounds for nuclear devices between 1946 and 1958. The testing produced close-in fallout debris that was contaminated with different radionuclides and which entered the aquatic environment. The contaminated lagoon sediments became a reservoir and source term of manmade radionuclides for the resident marine organisms. This report contains a summary of all the available data on the concentrations of ^{137}Cs, ^{60}Co and ^{207}Bi in flesh samples of reef and pelagic fish collected from Bikini and Enewetak Atolls between 1964 and 1995. The selection of these three radionuclides for discussion is based on the fact that these are the only radionuclides that have been routinely detected by gamma spectrometry in flesh samples from all fish for the last 20 y. Flesh from fish is an important source of food in the Marshallese diet. These radionuclides along with the transuranic radionuclides and ^{90}Sr contribute most of the small radiological dose from ingesting marine foods. Some basic relationships among concentrations in different tissues and organs are discussed. The reef fish can be used as indicator species because their body burden is derived from feeding, over a lifetime, within a relatively small contaminated area of the lagoon. Therefore, the emphasis of this report is to use this extensive and unique concentration data base to describe the effective half lives and cycling for the radionuclides in the marine environments during the 31-y period between 1964 and 1995. The results from an analysis of the radionuclide concentrations in the flesh samples indicate the removal rates for the 3 radionuclides are significantly different. ^{137}Cs is removed from the lagoons with an effective half life of 9–12 y. Little ^{60}Co is mobilized to the water column so that it is depleted in both environments, primarily through radioactive decay. The properties of ^{207}Bi are different at Enewetak and Bikini. At Enewetak the radionuclide is lost from the environment with an effective half live of 5.1 y. At Bikini only radioactive decay can account for the rate at which the radionuclide is lost from the lagoon. The difference in the binding properties of the sedimentary materials for ^{207}Bi among the two Atolls is not understood.**

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INTRODUCTION

Enewetak Atoll, located at about 11°21′N, 162°21′E, is the northwestern-most atoll in the Western (Ralik) chain of the Marshall Islands. The atoll originally consisted of a ring of 42 (39 remaining) low islands arranged on a roughly elliptical shaped reef, 40.2 by 32.2 km, with the elongated axis in the northwesterly direction. The atoll was one of the two sites in the northern Marshall Islands that was used by the United States as testing grounds for nuclear devices. At Enewetak, 19 of the 43 tests were made from barges anchored in the lagoon. The remaining tests included 2 air drops, 2 underwater tests, 7 ground surface tests and 13 tests with devices fixed to towers. Bikini Atoll, approximately 305 km east of Enewetak, was the first U.S. nuclear test site in the Pacific. It is located at 11°36′N, 165°22′E and consists of 23 coral islands surrounding a lagoon 35 km long, 21 km wide, and 630 km^2 in area. Most of the 23 tests conducted at Bikini were detonated on barges anchored in the lagoon or on the reef. Two tests were air drops, one was underwater, and three were ground surface explosions. Figures showing the Marshallese and U.S. names assigned during the testing program and locations of the islands at Enewetak Atoll and Bikini Atoll appear in other articles of this volume (Noshkin and Robison 1997; Robison et al. 1997).

The U.S. moratorium began on 31 October 1958, and marked the end of all nuclear testing at the atolls. The testing produced close-in fallout debris that was contaminated with different radionuclides and which entered the aquatic environment of the atolls. In the years that followed, the components associated with the lagoon sediments provided a reservoir and source term of manmade radionuclides for the resident marine organisms. These radionuclides are now remobilized, resuspended, assimilated, and transferred continuously within the Atoll environment by physical, chemical, and biological processes. Some of these processes at the atolls are discussed in McMurtry et al. (1985); Nelson and Noshkin (1973); Noshkin et al. (1974); Noshkin et al. (1975); Noshkin and Wong (1980); Schell et al. (1980); Schell (1987); and Spies et al. (1981). Of importance is the fact that the persistent activities are accumulated to different levels by indigenous terrestrial and aquatic plants and organisms that may be used as food by people. Uptake of different radionuclides by fishes can be directly from soluble species released to the water and from ingested material passing through the gut (Noshkin et al. 1987).

The first major aquatic survey that developed quantitative data for different radionuclides in fish from Enewetak and Bikini was conducted during 1964, 6 y after the moratorium (Welander et al. 1967; Welander 1969). Samples of fish were again collected by others at Bikini during 1969, 1970, 1972, 1974, 1975, 1976 and 1977 (Held 1971; Lynch et al. 1975; Schell et al. 1978; Nelson 1977) and at Enewetak in 1972–73 (Nelson and Noshkin 1973). Following the radiological aquatic survey at Enewetak in 1973 (Nelson and Noshkin 1973), a more detailed long term study was initiated to assess the behavior and fate of specific radionuclides in the aquatic environment. These studies were extended to Bikini Atoll in 1975. As part of this work a variety of fish was collected between 1975 and 1984 from the atolls for radionuclide analysis. Several reasons prompted these collections and the subsequent radiological analysis. The ultimate objective for obtaining radiological information was to use the data in estimating any potential radiological consequences to individuals from ingestion of indigenous marine foods. Hence, a major effort was devoted to dissections and analysis of the edible muscle tissue from a variety of fish. Other studies were made to evaluate the variability of radionuclides in families of fish; to define the major tissues or organs where radionuclides were concentrated by fish; and to develop concentration factors and relationships to assess the effective half time for some of the long-lived radionuclides using the resident non-migratory reef fish as indicators of environmental change.

The data generated from this effort showed that the radiological dose from manmade radionuclides in the marine food chain contribute less than 0.1% of the total 30-y integral dose equivalent at both Atolls (Robison 1973; Robison et al. 1987; Robison et al. 1997). The ingestion dose was derived principally from 3 gamma emitting radionuclides, ^{137}Cs, ^{60}Co and ^{207}Bi; the transuranic radionuclides, $^{238,239+240}$Pu, ^{241}Am; and ^{90}Sr. The largest contributor to the total marine dose was the ^{137}Cs accumulated in the edible flesh. The transuranic radionuclides and ^{90}Sr contributed little to the total dose from ingestion of marine foods. This collection program was phased out in 1985, but fish samples were again collected in the 1990's to verify the results of the original assessments and to determine what, if any, changes occurred in the concentrations of gamma emitting radionuclides and the transuranics in muscle tissues. Resources only permitted analysis of muscle tissue in these later samples. However, with these new data and results from earlier studies, a valuable data base was available for radionuclides in the flesh of different fish that span the 31-y period from 1964 to 1995. Some reef fish can be used as indicator species because their body burden is derived from feeding, over a lifetime, within a relatively small area containing the contamination. Decrease in radionuclide concentration in flesh can be used to estimate the effective decay constant and half-lives. The effective half life takes into account loss by physical decay and recycling mechanisms that reduce the available inventory of radionuclides to marine organisms. The general mathematical form of the exponential expression for the change over time in the amount of a radionuclide, using a indicator organism, can be found in Noshkin et al. (1975).

The 1964 and all subsequent data were generated by gamma spectrometry with NaI (Tl) crystals and different solid state Ge(Li) detectors and by radiochemical separations and using detection systems appropriate for the determination of specific radionuclides. Many fission products, activation products, and the transuranium elements were identified and measured in parts of fish. However, only 3 gamma emitting radionuclides, ^{137}Cs, ^{60}Co, ^{207}Bi were measurable in flesh samples by gamma spectrometry over the 31-y period. Most results for these radionuclides from our studies between 1974 and the present have not previously appeared in the literature. The transuranic radionuclides also persist in fish tissues but plutonium-americium results have been discussed in several other publications (Noshkin et al. 1981a; Noshkin et al. 1987; Noshkin et al. 1988; Schell et al. 1978; Schell 1987). There is also a summary of plutonium results in fish from Enewetak Atoll appearing in Noshkin and Robison (1997). Other radionuclides such as ^{90}Sr, ^{55}Fe, and ^{99}Tc may be present in specific tissues of fish but were found at concentrations so low that they contributed very little to the estimated dose and therefore were not measured in most samples on a regular basis. Naturally occurring radionuclides were also determined in many samples but are not discussed in this report.

This report summarizes both our data and those from other sources on the 3 major gamma emitting radionuclides in the flesh of reef and pelagic species of fish. Some basic relationships among concentrations in different tissues and organs will be presented. The concentrations measured in the flesh of several non-migratory reef species are used to estimate the effective half lives for ^{60}Co, ^{137}Cs, and ^{207}Bi during the 31-y period between 1964 and 1995.

SAMPLING AND PROCESSING FISH

Most fish collections on the reef at the Atolls were made using throw nets with assistance from Marshallese fishermen or with gill nets (Welander et al. 1967; Schell et al. 1978). Gill nets were not used after 1972, and reef fishing for our program was done exclusively with throw nets. Reef species are relatively abundant, easy to catch, and are therefore an important food source for the Marshallese. The fish were caught on the reef when and where they were sighted in the surf. Therefore, fish may be collected from different regions of an island in any given year. Variability in radionuclide concentration can then be expected as a function of geographical location even on the same island. However, this "catch when available" method of fishing probably best mimics the manner by which these marine foods are derived by the

Marshallese for consumption. Noshkin and Robison (1997) show what the effects of different fishing locations have on the concentration of ^{137}Cs accumulated in the flesh of surgeonfish from Runit Island of Enewetak Atoll. The other category of fish include larger resident and migratory predator species that were usually more difficult to catch with sport fishing gear while trolling in the lagoon.

Except for the larger fish it was usual to bulk flesh and specific tissues and organs separated from the species collected from an island on any given day. The samples were homogenized, dried (or ashed) and transferred to suitable containers for analysis on gamma spectrometers. A number of samples were then selected for radiochemical analysis of different beta or alpha emitting radionuclides. The common and scientific names for the fish that were eventually processed to determine radionuclides *only* in muscle tissue are shown in Tables 1 and 2 with the sampling locations and a cross reference island locator ID number that is used throughout this report. The concentrations of ^{137}Cs, ^{60}Co, and ^{207}Bi determined in flesh tissue of fish from Enewetak and Bikini appear in the appendices and represent the results in over 300 samples from 4,470 fish. All results are decay corrected to date of sample collection. A cursory examination of the appendices reveals that concentrations in flesh vary with species, over time, and with geographical location in each Atoll. Compositing the tissues from the same species masked any differences in concentration related to weight (size or age) or sex.

Tables 1 and 2 and the Appendices A and B show that 3 reef species, surgeonfish (2nd trophic level), mullet (2nd trophic level), and goatfish (3rd trophic level), are represented in most collections. Obviously, then, these reef fish are easily caught but they are also preferred in the Marshallese diet. Mullet and goatfish were often caught in the same net cast at an island indicating that both species move and feed together. A

Table 1. Fishing sites at Bikini Atoll since 1964 where muscle tissue was separated for analysis from the species indicated.

Island ID	Marshallese Name	Aug[a] 1964	May[b] 1970	May[c] 1972	Nov[d] 1972	Dec[d,e] 1974	Apr[e] 1975	Jul[d] 1976	Jan[f] 1977	Oct[d] 1977	Nov[f] 1978	Sep[f] 1980	Feb[f] 1981	Jun[f] 1982	Aug[f] 1983	Sep[f] 1984	Dec 1992	Nov 1994
B-1	Nam	gr,n,s,t[g]	g	sn	u			cr,n,sn	cr,n	n	cr,n,g,s		cr		cr,n,s,g	g,u,rr	g,cr,n,s	c,n
B-2	Iroij								cr									
B-3	Odrik	bo,gr,j,s,t,w																
B-5	Aomen				g,n,p,q,s						cr,n,s,g		cr,s,g,p	n	cr,s		g,n,s	g,p
B-6	Bikini	sn			p,s,n						s,g	cr,g,sn	cr,n	n	g	cr,g	g,cr,s	g,s
B-9	Enealo					sn												
B-10	Rojkere				g				n		s,g							
B-12	Eneu	da,gr,n,s			p,r,s		gr,p		cr		n,s,g				s,g	n,g		
B-13	Aerokoj								cr		cr,s,g							
B-15	Lele	l								g								
B-16	Eneman																	
B-17	Enidrik				n,p,s,u				n		cr,n,g,p				s	n		
B-21	Oroken																	
B-22	Bokoetoktak													u				
B-23	Borkdrlul	gr,sn,s,t			n,s						n,g							
lagoon				tn	ra,bo	m,s		s		s,bo,ba,m,u	snj,m		m			sn,bo		

[a] Welander et al. (1967)
[b] Held (1971)
[c] Lynch et al. (1975)
[d] Shell et al. (1978)
[e] Nelson (1977)
[f] Noshkin et al. (1988)
[g] ba = barracuda (*Sphyraena sp.*)
bo = bonito (*Euthynnus affinus*)
cr = mullet (*Crenimugil crenilabis*)
da = damselfish (*Abudefduf biocellatus*)
g = goatfish (*Mulloidichthys samoensis*)
gr = grouper (*Epinephelus merra*)
j = jack (*Caranx sp.*)
l = ladyfish (*Albula vulpes*)
m = mackerel (*Grammatorcynus billineatus*)
n = mullet (*Neomyxus chaptalii*)
p = parrotfish (*Scarus sordidus*)
q = queenfish (*S. sancti-petri*)
rr = rainbow runner (*Ellagatis bipinnulatus*)
s = convict surgeon (*Acanthurus triostegus*)
sn = snapper (*Lutjanus bohar*)
t = triggerfish (*Rhineacanthus ractangulus*)
tn = tuna (*Gymnosarda nuda*)
u = ulua (*Caranx melanpygus*)
w = wrasse (*Halichoeres trimaculatus*)

Table 2. Fishing sites at Enewetak Atoll since 1964 where muscle tissue was separated for analysis from the species indicated.

Island ID	Marshallese name	Aug[a] 1964	Nov[b] 1972	Apr–May 1976	Jun 1977	Mar 1978	Nov 1978	Sept 1980	July 1981	June 1982	Aug 1983	Sept 1984	Nov 1993	Feb 1994	Nov 1994	May 1995
E-2	Bokombako	bu,da,gr,sn,sq,s,t,w[c]	cr	cr,s			g,n,s				g,cr,u					
E-5	Bokinwotme	gr,n,p,s,t														
E-9	Boken		cr,sn			cr			g,cr,s							
E-10	Enjebi	gr,j,cr,p,s,t	cr,p	n	n		g,p,s	sn			g,gr,cr,n,sn,s,t	bo,g,u	g,s	ft,g,pa,s	g,s	g,s
E-19	Aomon			n,s	n		s	bo,cr					s			
E-20	Bijile		cr,p,sn,u										g			
E-24	Runit	g,h,s	gr,p,tn,u	n,s			cr,s	g,cr,n,p,sn,s	g,n,s	n,s	ba,cr,n,sn,s		g,s	n,s	ft,g,p,s	g,cr,n,s
E-33	Japtan		p	g,cr,s												
E-35	Medren		sn,u													
E-37	Enewetak		gr,p,sn,u	cr,s			s									
E-38	Ikuren	gr,s	sn	s								cr				
E-39	Mut		p													
E-43	Biken	g,gr,j	cr,p	cr												
E-45	Drekatimon							ba,m,u			m,u	m,u				

[a] Welander et al. (1967)
[b] Nelson and Noshkin (1973)
[c] ba = barracuda (*Sphyraena sp.*)
bo = bonito (*Euthynnus affinus*)
bu = butterflyfish (*Chaetodon auriga*)
cr = mullet (*Crenimugil crenilabis*)
da = damselfish (*Abudefduf biocellatus*)
ft = flagtail (*Kuhlia taeniura*)
g = goatfish (*Mulloidichthys samoensis*)
gr = grouper (*Epinephelus merra*)
h = halfbeak (*Hemirhamphus laticeps*)
j = jack (*Caranx sexfasciatus*)
m = mackerel (*Grammatorcynus bilineatus*)
n = mullet (*Neomyxus chaptalii*)
p = parrotfish (*Scarus sordidus*)
s = convict surgeon (*Acanthurus triostegus*)
sn = snapper (*Lutjanus bohar*)
t = triggerfish (*Rhineacanthus ractangulus*)
tn = tuna (*Thunnus albacares*)
u = ulua (*Caranx melanpygus*)

brief description of the feeding habits can be found elsewhere in this volume (Noshkin and Robison 1997). The feeding habits and trophic level assignments of the remaining reef and pelagic fish shown in Tables 1 and 2 and in the Appendices can be found elsewhere (Hiatt and Strasburg 1965; Noshkin et al. 1988; Welander et al. 1967).

RESULTS AND DISCUSSION

Radionuclides detected in parts of different fish from the atolls

In the 1964 study, sodium iodide detectors were used with multichannel analyzers for non-destructive analysis of the different samples. Spectrum stripping methods were used to determine the levels of several gamma emitting radionuclides accumulated by different fish (Welander et al. 1967). Chemical separations were used to isolate other beta and alpha emitting radionuclides from the samples. Data were generated for the gamma emitting radionuclides ^{54}Mn, ^{57}Co, ^{60}Co, ^{65}Zn, ^{106}Ru, ^{125}Sb, ^{137}Cs and ^{207}Bi (and natural ^{40}K). Radiochemical separations provided information on ^{55}Fe (decay by EC), ^{90}Sr, $^{239+240}$Pu and $^{102\,m}$Rh in the fish. The presence of ^{144}Ce, ^{155}Eu and $^{110\,m}$Ag was verified in some samples. ^{207}Bi had been previously reported in environmental samples from the atolls (Lowman and Palumbo 1962), but it was during this survey that the first determination of the radioisotope was made in fish samples. It was present in fish from Enjebi Island, Enewetak Atoll, in concentrations far exceeding those at other islands of either atoll (Welander et al. 1967). At this time ^{106}Ru and ^{125}Sb were below detection limits in muscle tissue of all fish from Bikini and the photopeak from ^{54}Mn was not evident in any flesh samples from Enewetak. Of the remaining gamma emitting radionuclides only ^{137}Cs, ^{60}Co and ^{207}Bi were detected with regularity.

Samples of fish were again collected by others during sampling programs at Bikini in 1969, 1970, 1972, 1974,1975, 1976 and 1977 (Held 1971; Lynch et al. 1975; Nelson 1977; Schell 1978) and at Enewetak in 1972–1973 (Nelson and Noshkin 1973). Samples from this latter survey (and from the 72, 74, 75 76 and 77 Bikini surveys) were eventually dried and/or ashed and analyzed non-destructively on Ge(Li) detectors at different laboratories. For these latter programs it was possible to resolve, without the spectral interference common to NaI, the concentrations of any gamma emitting radionuclides present in the samples that exceeded detection limits. By 1974 the radionuclides ^{54}Mn, ^{57}Co, ^{144}Ce, ^{110m}Ag, ^{95}Zr and ^{106}Ru had sufficiently decayed so that they were only occasionally found in viscera, liver or gut content samples from specific fish. With the improved Ge(Li) detection systems, the gamma emitting radionuclides ^{241}Am, ^{101}Rh, ^{134}Cs, ^{108m}Ag, and ^{152,154}Eu were identified in parts of some fish along with ^{40}K, ^{60}Co, ^{102m}Rh, ^{125}Sb, ^{137}Cs, ^{155}Eu and ^{207}Bi previously found in the 1964 samples (Welander et al. 1967). Wet chemical separation methods were used with beta-alpha detection instruments to measure ^{241}Pu and ^{238}Pu in addition to ^{90}Sr, ^{55}Fe, ^{63}Ni, and $^{239+240}$Pu. Mass spectrometry was used to determine levels of ^{239}Pu and ^{240}Pu in parts of some of the fish (Noshkin 1980). We identified and quantified levels of ^{99}Tc, ^{242,244}Cm and ^{113m}Cd (Noshkin et al. 1981b) in species of fish collected during the late 1970's. Concentrations of ^{242,244}Cm and ^{99}Tc in flesh were a few percent of the respective $^{239+240}$Pu concentration. The detection of ^{242}Cm ($t_{1/2}$ = 163 d) in environmental samples, 20 y after the end of testing, must indicate the presence of the parent radionuclide, ^{242m}Am, in the environment.

By 1974, only the gamma emitting radionuclides, ^{60}Co and ^{137}Cs, were evident in the majority of muscle tissue samples from reef and pelagic species. ^{207}Bi was poorly concentrated or below detection limits in muscle from most reef fish except the goatfish, parrotfish, and the larger pelagic species from the lagoon (see Appendices). By the late 1970's to the early 1980's, only ^{155}Eu, ^{108m}Ag, ^{102m}Rh were the only other gamma emitters, in addition to ^{60}Co, ^{137}Cs and ^{207}Bi, above detection limits in separated samples of viscera, liver, or gut content (Noshkin et al. 1988; Schell et al. 1978). Isotopes from this former group of radionuclides were never in concentrations above detection limits in large samples of flesh bulked for analysis by gamma spectrometry. In collections made during the 1990's, only the flesh was separated from fish and analyzed. At both atolls ^{207}Bi remained below detection limits in muscle tissue from all reef fish except goatfish. Levels of ^{137}Cs diminished to detection limits in mullet and goatfish at many islands, and ^{60}Co was found everywhere low in concentration or below our limit of detection.

Tissue and organ concentrations of ^{207}Bi, ^{60}Co, and ^{137}Cs and geographical relationships

The larger migratory pelagic species cannot be used as indicators for changes in the availability of the radionuclides over time. The most useful data to assess the temporal change in concentration is from reef species that were repeatedly sampled over time from the same general locations at the Atolls. Therefore, this discussion will be limited to an assessment of the concentrations in 3 common reef species—mullet, surgeonfish, and goatfish—but the appendices can be referenced for levels in the flesh of the other species of fish. Representative whole fish concentrations for ^{137}Cs, ^{60}Co, and ^{207}Bi in mullet, surgeonfish, and goatfish from 1978 are reconstructed from tissue and organ concentration data and the percentages of the respective tissues to whole body weight (Noshkin et al. 1987). Results are shown in Table 3 and are used to compute the percent of the whole body activity associated with the tissues shown. The concentrations determined in the viscera samples are regrettably less descriptive than those for the other tissues because of the matrix of organs and tissues represented. These include large and small intestines with contents, stomach wall, spleen, kidney and mesenteries. The radionuclide concentration of the viscera could often vary with the amount of material in the intestines that often contained quantities of bottom sediment (especially the mullet) labeled with the radionuclide.

Concentrations of ^{137}Cs ($t_{1/2}$=30.1 y) in flesh and viscera of fish are comparable but because of the larger mass, most of the radionuclide accumulated by fish is found associated with the edible flesh; the lowest percentages are associated with bone and liver. Concentrations in the flesh of the three species are approximately equivalent to the concentration in the reconstructed whole body. However, concentrations associated with surgeonfish (see Appendices) were always greater than levels in flesh of goatfish and generally exceeded or were equivalent to the levels in mullet collected at the same time from different islands of the Atolls. The surgeonfish are the better environmental indicators for ^{137}Cs levels. At Bikini, higher concentrations of ^{137}Cs were generally found in flesh of reef fish from the northwest quadrant of the atoll (B-1 to B-5), and the lowest levels were associated with reef species from the eastern reef. At Enewetak, generally higher concentrations were measured in the reef fish from the northern half of the atoll (E2-E-24) and lowest levels were found associated with reef species from the southeastern and southern reef of the atoll.

In 1982, ocean fish fillets purchased from stores in the Chicago area of the United States, contained 0.85±0.07 Bq kg^{-1} of ^{137}Cs derived from global fallout (Karthunen 1982). The appendices show that after 1978 the mean concentrations of ^{137}Cs in reef fish from islands B-10 to B-23 at Bikini and from E-33 to E-38 at Enewetak were comparable to the fallout levels in the U.S. store-purchased fish.

Between 1958 (the end of testing) and 1994, ^{60}Co levels in the environments decreased by a factor of 30 from radioactive decay alone ($t_{1/2}$=5.26 y). However, measurable concentrations are still found in fish collected during the 1990's. From 20 to 50% of the body burden of ^{60}Co is present in the muscle tissue with most of the remainder distributed among the liver, skin, and viscera. Unlike ^{137}Cs, concentrations of ^{60}Co in the flesh of mullet and goatfish were consistently higher than levels in surgeonfish simultaneously caught at the same islands. Therefore, the goatfish and mullet are better environmental indicator species for changes in ^{60}Co concentrations in the lagoon environment. The levels of ^{60}Co in the flesh of the reef fish from different regions of the atolls vary in the same manner as ^{137}Cs and generally

Table 3. Concentrations in tissues and percent of whole body concentration for 3 reef species.

Island locator #	Common name	Muscle[a] Bq kg^{-1}	%[c]	Bone[a] Bq kg^{-1}	%[c]	Skin[a] Bq kg^{-1}	%[c]	Liver[a] Bq kg^{-1}	%[c]	Viscera[a] Bq kg^{-1}	%[c]	Gut contents[a] Bq kg^{-1}	%[c]	Reconstructed[b] whole fish concentration Bq kg^{-1}	Muscle/whole fish activity ratio
^{137}Cs															
B-1	Mullet[d]	14.7	67	0.9	0.5	8.2	9	13.6	1.0	15.3	13	22.0	1.2	12.9	1.14
E-10	Mullet	7.8	38	1.1	0.6	10.1	12	3.7	0.3	36.0	33	43.5	2.6	11.9	0.65
B-6	Surgeonfish	6.2	67	0.2	0.2	10.5	20	3.5	0.4	5.5	6	5.8	0.7	6.1	1.01
E-24	Surgeonfish	14.4	72	0.7	0.5	13.3	12	4.6	0.2	15.8	8	21.5	1.1	13.2	1.09
B-1	Goatfish	5.5	74	2.5	4	4.1	10	4.0	0.3	4.0	5	5.1	0.1	4.9	1.11
E-2	Goatfish	1.5	75	0.1	0.9	1.0	8	0.9	0.3	1.8	9	2.1	0.1	1.3	1.13
															mean = 1.03 ± 0.12
^{60}Co															
B-1	Mullet	33.2	39	32.6	4.4	72.7	20	742.1	13	69.0	15	17.7	0.2	50.7	0.65
E-10	Mullet	1.3	17	4.6	7.4	9.6	32	81.4	17	6.5	17	4.0	0.6	4.3	0.30
B-10	Surgeonfish	1.0	36	1.3	6.1	2.8	19	29.9	12	4.4	17	9.4	3.8	1.7	0.55
E-2	Surgeonfish	3.0	50	3.3	6.4	8.3	24	39.2	6.7	1.9	3	25.2	4.3	4.1	0.75
B-1	Goatfish	21.2	33	17.8	3.3	61.8	17	951.1	9	207.3	31	133.6	0.2	43.2	0.49
E-10	Goatfish	13.2	29	5.4	1.4	36.2	14	306.4	4.2	200.1	44	45.3	0.1	29.8	0.44
															mean = 0.53 ± 0.12
^{207}Bi															
B-1	Mullet	0.1	18	0.1	2.1	0.1	4	4.3	8.1	2.0	45	4.6	6.7	0.5	0.30
E-24	Mullet	0.0	1	0.2	0.5	0.1	0	2.5	0.9	15.5	66	37.2	10.1	2.6	0.02
B-6	Surgeonfish	0.0	14	0.1	9.2	0.1	14	3.8	23	0.5	30	0.7	4.3	0.1	0.21
E-24	Surgeonfish	0.0	5.6	0.3	5.6	0.1	4	19.9	36	2.2	36	3.4	6.2	0.4	0.08
B-17	Goatfish	8.1	67	4.4	4.4	9.0	13	26.0	1.3	9.1	7	2.9	0.0	8.0	1.00
E-10	Goatfish	241.9	71	65.6	2.3	173.0	9	276.4	0.5	354.2	10	45.3	0.0	224.9	1.08
															mean mullet & surgeonfish = 0.15 ± 0.11
															mean goatfish = 1.04 ± 0.04

[a] Muscle, skin, bone, liver, viscera and gut contents account for 93–95% of total fish weight.
[b] Bq kg^{-1} whole fish = [Σ (Bq kg^{-1} wet tissue) × (% tissue of whole body wt)] × (Σ % tissue of whole body wt)$^{-1}$.
[c] Percent of total body activity in respective tissue or organ.
[d] Mullet = Crenimugil crenilabis.

reflect the differences found in the distribution of activities associated with lagoon sediments.

Most striking were the differences found for ^{207}Bi ($t_{1/2}$ = 32.2 y) among the tissues of the reef species. In mullet and surgeonfish, ^{207}Bi was usually below detection limits by gamma spectrometry in many parts separated from the fish. The radionuclide was consistently detected in the muscle and other organs of goatfish and the pelagic lagoon fish. About 70% of the whole body activity of ^{207}Bi in goatfish is associated with flesh whereas less than 20% (when detected) is found in the flesh of mullet and surgeonfish. Highest levels were consistently found in flesh of goatfish collected on the reef of Enjebi Island (E-10), Enewetak Atoll. Levels in comparable species from islands of Enewetak Atoll generally exceeded concentrations at Bikini Atoll. Goatfish are clearly the better indicator among different fish for ^{207}Bi levels in the lagoon environment.

Previous estimates of the effective half-life of ^{137}Cs, ^{60}Co, and ^{207}Bi using reef fish concentration data

Radiological dose assessments for the marine food chain from ingestion of marine food have been made assuming that the time necessary to reduce the concentrations in the food (and the environment) by a factor of two is related only to the radioactive half-life of a radionuclide. Clearly, if other processes are operating in the environment that reduced the availability of a radionuclide, the dose received by individuals over time would be less. The concentrations in flesh from the reef fish are used to describe the change in the activity levels of ^{137}Cs, ^{60}Co, and ^{207}Bi in the environment over a 30-y period of time.

There have been other attempts to model the changes in environmental concentrations using radiological data retained in fish parts. During the 1972–1973 radiological survey of Enewetak, Nelson and Noshkin (1973) compared the activity levels in 5 samples of viscera from surgeonfish with those in samples from fish collected at the same islands of the atoll in 1964. The average fraction of ^{60}Co and ^{207}Bi found in 1972 viscera was 0.11±0.04 and 0.32±0.19, respectively, of the amounts measured in 1964. The effective half lives computed from these data were 2.6±0.9 y for ^{60}Co and 5.0±3.0 y for ^{207}Bi.

Schell (1987) used concentration data in the viscera of mullet (*Neomyxus chaptalii*) collected at Nam (B-1) Island, Bikini Atoll, between 1964 and 1977 to assess the combined effect of physical decay and removal by lagoon processes. The value of the slope from a least square fit of the natural log (ln) of the respective concentration with time (in years), yielded effective half lives for ^{137}Cs, ^{60}Co, and ^{207}Bi of 4.1±0.5, 3.0±0.4, and 6.3±1.7 y, respectively. The values for ^{60}Co and ^{207}Bi are in generally good agreement with the values determined at Enewetak and tend to indicate that, over the time period, the decline of these radionuclides within the lagoons was more rapid than radioactive decay alone.

Effective half-life of ^{137}Cs, ^{60}Co, and ^{207}Bi using concentration data in flesh of reef species

The data in the Appendices were treated in several manners. Only measurable radionuclide concentrations with less than 100% counting error for mullet, convict surgeonfish, and goatfish were considered. No error was quoted for the measurements associated with the 1964 collections (Welander et al. 1967). A 10% error was arbitrarily assigned to each reported concentration. Fallout background levels of ^{137}Cs were estimated in the flesh from values in species from other Northern Marshall Atolls (Noshkin et al. 1987), concentration factors, and equatorial water concentrations determined over time. These values ranged from 0.3 to 0.9 Bq kg^{-1} and varied with the species over time of collection. All ^{137}Cs data were corrected before plotting the results to estimate the effective decay constants. When sufficient measurements of a radionuclide were available for fish from one island, the data were plotted on a semilog graph (using a spreadsheet program), essentially in the manner used by Schell (1987), to determine the decay constant using a least square fitting (LSF) procedure. All applicable data points from the collections made between 1964 and 1995 were used to generate the curves. An example is shown in Noshkin and Robison (1997) where the ^{137}Cs levels in the flesh of convict surgeonfish from North Runit Island, Enewetak Atoll, are plotted against the date of collection. A least square fit to the data yields a slope (λ) with a value of 0.104 ± 0.012 y^{-1}. The error term is the uncertainty in the estimation of the slope. The computed effective decay constant (λ) consists of a physical (λ_r) and environmental (ecological = λ_e) decay constant. The effective and ecological half-lives ($t_{1/2}$, $t_{1/2e}$) can be computed. The latter half-life requires use of the physical half-lives for the radionuclides that were provided in a previous section and given again in Table 4. This procedure was followed at several other islands where there was sufficient long term data for a specific radionuclide. The computer generated results are shown in Table 4.

There were clearly differences in radionuclide concentration measured in the same species collected from different parts of the Atolls during any one period and over time. It was therefore impossible to construct a single plot, for example, to show all ^{137}Cs concentrations in surgeonfish at Enewetak over time. It was, however, possible to normalize concentrations to a value in the

Table 4. Effective and ecological decay constants and half-lives of ^{137}Cs, ^{60}Co and ^{207}Bi determined from concentrations in flesh of fish from locations within Enewetak and Bikini Atolls. The error is the uncertainty in the estimation of the value for the constants.

Location	Data used	Data points	Isotope	Radiological half-life (y)	λ (y^{-1})[a]	$t_{1/2}$[a] (y)	λe (y^{-1})[b]	$t_{1/2e}$[b] (y)
Enewetak Atoll								
E-24	Surgeonfish	13	^{137}Cs	30.00	0.104 ± 0.012	6.7 ± 0.7	0.081 ± 0.012	8.6 ± 1.3
E-10	Surgeonfish	9	^{137}Cs	30.00	0.063 ± 0.011	11.0 ± 1.9	0.040 ± 0.011	17.3 ± 4.8
E-2	Surgeonfish	4	^{137}Cs	30.00	0.044 ± 0.024	15.8 ± 8.6	0.021 ± 0.024	33 ± 38
E-2,-10,-24	Surgeonfish	26[c]	^{137}Cs	30.00	0.069 ± 0.010	10.0 ± 1.4	0.046 ± 0.010	15.1 ± 3.3
All locations	All reef fish	58[c]	^{137}Cs	30.00	0.060 ± 0.010	11.6 ± 1.9	0.037 ± 0.010	18.7 ± 5.1
E-24	Surgeonfish	7	^{60}Co	5.26	0.195 ± 0.022	3.6 ± 0.4	0.062 ± 0.022	11.2 ± 4.0
E-24	Goatfish	6	^{60}Co	5.26	0.147 ± 0.067	4.7 ± 2.1	0.015 ± 0.067	46 ± 205
E-10	Goatfish	6	^{60}Co	5.26	0.143 ± 0.027	4.8 ± 0.9	0.011 ± 0.027	63 ± 155
E-2	Surgeonfish	4	^{60}Co	5.26	0.190 ± 0.010	3.6 ± 0.2	0.058 ± 0.010	12.0 ± 2.1
All locations	All reef fish	58[c]	^{60}Co	5.26	0.173 ± 0.024	4.0 ± 0.6	0.041 ± 0.024	17 ± 10
E-24	Goatfish	7	^{207}Bi	32.20	0.093 ± 0.018	7.4 ± 1.4	0.071 ± 0.018	9.8 ± 2.5
E-10	Goatfish	8	^{207}Bi	32.20	0.208 ± 0.068	3.3 ± 1.1	0.186 ± 0.068	3.7 ± 1.4
All locations	Goatfish	26[c]	^{207}Bi	32.20	0.136 ± 0.025	5.1 ± 0.9	0.114 ± 0.025	6.1 ± 1.3
Bikini Atoll								
B-1	Surgeonfish	5	^{137}Cs	30.00	0.103 ± 0.047	6.7 ± 3.1	0.080 ± 0.047	8.7 ± 5.1
B-5	Surgeonfish	4	^{137}Cs	30.00	0.064 ± 0.017	15.6 ± 4.1	0.041 ± 0.017	17 ± 7
B-6	Surgeonfish	4	^{137}Cs	30.00	0.034 ± 0.024	20 ± 14	0.011 ± 0.024	>60
All locations	Surgeonfish	16[d]	^{137}Cs	30.00	0.073 ± 0.022	9.5 ± 2.9	0.050 ± 0.022	14 ± 6
B-1	All reef fish	22[d]	^{137}Cs	30.00	0.097 ± 0.023	7.1 ± 1.7	0.074 ± 0.023	9.4 ± 2.9
B-1	All reef fish	11[d,e]	^{137}Cs	30.00	0.126 ± 0.034	5.5 ± 1.5	0.103 ± 0.034	6.7 ± 2.2
All locations	All reef fish	54[d]	^{137}Cs	30.00	0.079 ± 0.015	8.8 ± 1.7	0.056 ± 0.015	12.4 ± 3.3
B-1	All reef fish	20[d]	^{60}Co	5.26	0.151 ± 0.027	4.6 ± 0.8	0.019 ± 0.027	36 ± 51
B-1	All reef fish	12[d,e]	^{60}Co	5.26	0.230 ± 0.039	3.0 ± 0.5	0.098 ± 0.039	7.1 ± 2.8
All locations	All reef fish	53	^{60}Co	5.26	0.131 ± 0.013	5.3 ± 0.5	0.000 ± 0.013	>53
B-1	Goatfish	4	^{207}Bi	32.20	0.025 ± 0.009	28 ± 10	0.003 ± 0.009	>58
All locations	Goatfish	11	^{207}Bi	32.20	0.023 ± 0.009	30 ± 12	0.001 ± 0.009	>77

[a] Effective decay constant and half-life.
[b] Ecological decay constant and half-life.
[c] Data normalized to 8/83.
[d] Data normalized to 7/78.
[e] Only data between 1964 and 1978 used for comparison with values generated using fish viscera samples (Schell 1987).

same species from an island measured on a common collection date. Relative concentrations could then be plotted against time using measurements in all reef species from one island or for all species from the entire Atoll. At Enewetak, a number of measurements for the 3 species from islands E-2, E-10, and E-24 were made in August 1983. At Bikini, common collections were made at B-1, B-5, B-6, B-12, and B-17 on November 1978. For example, consider the data entries for ^{60}Co in fish from island B-1, abstracted from the Appendix, shown in Table 5. Concentration measured in flesh of the different fish during the November 1978 collections are shown in bold type. Goatfish data from all collections was divided by 6.70 Bq kg^{-1} to generate the set of relative concentration values shown in column 6 of Table 5. Likewise, the Mullet-C (*Crenimugil crenilabis*), Mullet-N (*Neomyxus chaptalii*), and Surgeonfish (*Acanthurus triostegus*) measurements were divided by the respective concentration (shown in bold type) determined in the species collected in November 1978. The normalized values are shown in column 6, and column 7 contains the standard deviation computed for the ratio. This procedure was followed with the fish data from other islands. At Enewetak concentrations were normalized to the values from the August 1983 collections. The relative concentration ratios were transferred to semilog plots and a LSF procedure was applied to the data sets to assess the effective decay constants (λ) and the uncertainty in the estimated value of the constant. Plots for relative (normalized) concentrations of ^{137}Cs in all reef fish from Bikini and Enewetak over time are shown in Figs. 1 and 2. A best fit to the results yields the trend line shown in the figures and the computed effective decay constants. Regression lines from a best fit to the normalized ^{60}Co data in reef fish from the two Atolls are shown in Fig. 3.

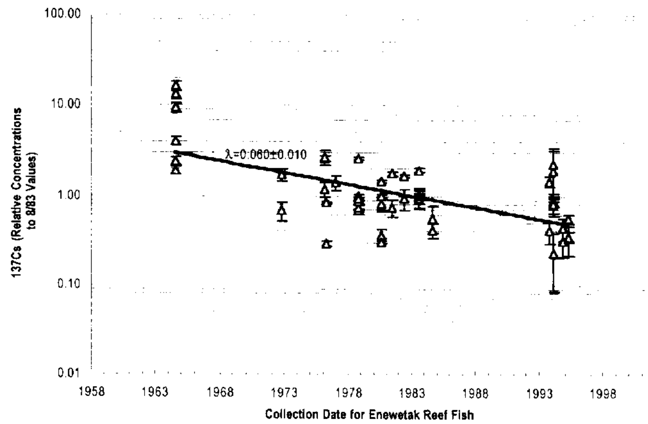

Fig. 1. Relative concentration of ^{137}Cs in flesh of reef fish from Enewetak Atoll as a function of collection time. Concentration data are normalized to values in fish from August 1983 collections. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendix A.

Fig. 4 shows the relative change for ^{207}Bi in goatfish (the only reef species with consistently detected concentrations in the flesh) from Enewetak. The computed decay constants and the respective half-lives from these analyses and others (not shown with accompanying figures in this report to conserve space) along with calculated uncertainties are summarized in Table 4. Values for correlation coefficients (R^2) of the different regression equations ranged from 0.5 to 0.9 showing moderate to strong correlation among the results.

The effective decay constants were also computed using fish data from 1964 to 1978 at Nam Island to determine if the flesh concentrations provided compara-

Table 5. Data from Appendix B for ^{60}Co concentration in flesh of reef fish from island B-1, Bikini Atoll.

Island	Common name	Collection date	Concentration Bq kg^{-1} wet	Error as % of measured concentration	Concentration normalized to amount measured in 11/78	± Error in relative ratio
B-1	Goatfish	May-70	101.39	3	4.78	0.15
B-1	Goatfish	Nov-78	**21.19**[a]	1	1.00	0.01
B-1	Goatfish	Aug-83	6.70	4	0.32	0.01
B-1	Goatfish	Dec-92	6.13	10	0.29	0.03
B-1	Mullet-C	Jul-76	12.33	7	0.37	0.03
B-1	Mullet-C	Jan-77	11.24	2	0.34	0.01
B-1	Mullet-C	Nov-78	**33.21**[a]	1	1.00	0.01
B-1	Mullet-C	Feb-81	8.22	3	0.25	0.01
B-1	Mullet-C	Aug-83	2.53	26	0.08	0.02
B-1	Mullet-N	Aug-64	798.52	10	50.19	5.04
B-1	Mullet-N	Jul-76	15.68	6	0.99	0.06
B-1	Mullet-N	Jan-77	18.80	3	1.18	0.04
B-1	Mullet-N	Oct-77	13.12	7	0.82	0.06
B-1	Mullet-N	Nov-78	**15.91**[a]	1	1.00	0.01
B-1	Mullet-N	Dec-92	6.48	13	0.41	0.05
B-1	Surgeonfish	Aug-64	67.63	10	7.84	0.79
B-1	Surgeonfish	Nov-78	**8.63**[a]	1	1.00	0.01
B-1	Surgeonfish	Aug-83	1.24	6	0.14	0.01
B-1	Surgeonfish	Aug-83	1.64	7	0.19	0.01
B-1	Surgeonfish	Dec-92	1.87	20	0.22	0.04

[a] November 1978 data in bold (see text).

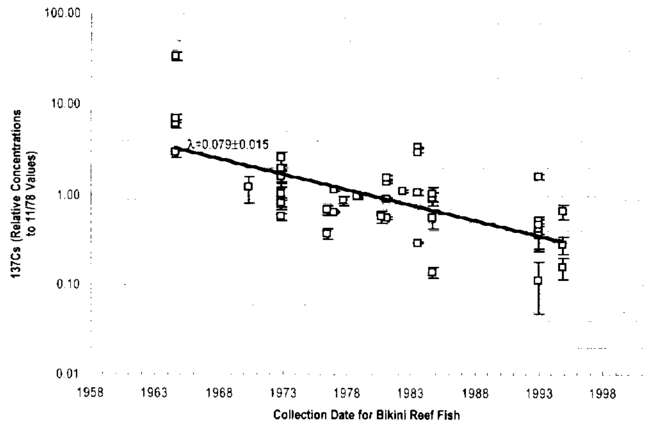

Fig. 2. Relative concentration of ^{137}Cs in flesh of reef fish from Bikini Atoll as a function of collection time. Concentration data is normalized to values in fish from November 1978 collections. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendix B.

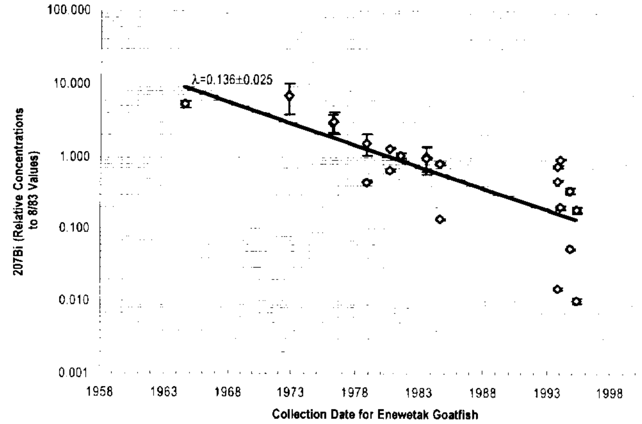

Fig. 4. Relative concentration of ^{207}Bi in flesh of reef fish from Enewetak Atoll as a function of collection time. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendix A.

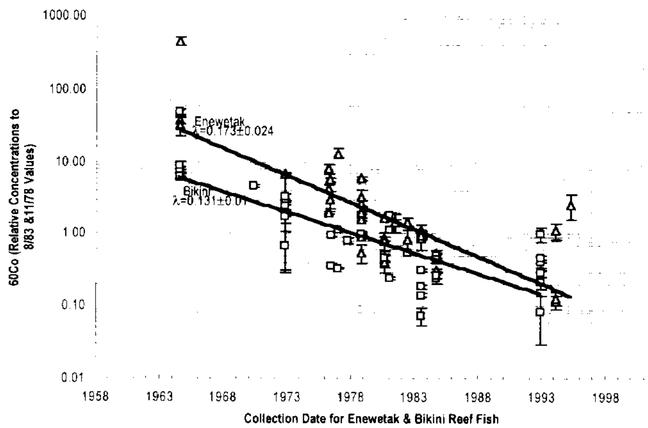

Fig. 3. Relative concentrations of ^{60}Co in flesh of reef fish from both Enewetak and Bikini as a function of collection time. Regression lines showing best fit to change in concentration with tie at each Atoll are shown. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendices A and B.

ble decay constants to the values derived from viscera samples by Schell (1987) in his analysis. These values are identified in Table 4 for ^{137}Cs and ^{60}Co.

Surgeonfish were the best indicator species for ^{137}Cs. Results at Enewetak in Table 4 indicate that the effective rate for ^{137}Cs removal might be more rapid at Runit (E-24), located on the eastern rim of the Atoll, than at islands E-2 and E-10 in the northwest part of the Atoll. One could argue that the physical form of material with bound ^{137}Cs is different over areas of the lagoon and release of the radionuclide occurs at different rates over time. However, the 3 values are within 2 sigma of the mean λ (0.069 ± 0.010) computed from the normalized surgeonfish measurements from the three islands. This later value was equivalent to the effective decay constant using the normalized data from the 58 measurements in reef fish from all locations. The best estimate for the effective half-life of ^{137}Cs in the lagoon at Enewetak is therefore about 12 ± 2 y. The ecological half-life is 19 ± 5 y. Subtle differences that may be related to geography and/or test location are masked by the error derived from the analysis.

At Bikini the surgeonfish results also tended to show a geographical dependence on the computed effective half-live from island B-1 in the northwest to B-6 on the eastern rim of the Atoll. As with Enewetak, all 3 values are within 2 sigma of the mean computed from surgeonfish at all lagoon locations. The error term again masks any difference with might be attributed to geography. The effective half-life using muscle data from all fish collected at Nam (B-1) prior to 1978 was 5.5 ± 1.5 y. This is in good agreement with the value of 4.1 ± 0.5 found by Schell (1987) using data for mullet viscera. A somewhat longer effective half-life (7.1 ± 1.7) results when all data are used to generate the effective decay constant. The difference between the computed half lives could indicate the rate of ^{137}Cs release from the environmental sedimentary components has diminished since 1978. This value is also in good agreement with the half-life of 9 ± 2 y computed from the 54 data points for all reef fish from all lagoon locations. Although it is inferred from the results, it would be difficult to argue strongly (because of the uncertainty) that there is a difference in the effective and ecological half-lives of ^{137}Cs between islands or the Atolls of Bikini and Enewetak. An effective half live of from 9 to 12 y indicates ^{137}Cs is removed from the lagoon by processes that exceed the rate of radiological decay alone.

Results from different species generate similar effective half lives. For example, there is good agreement seen in the computed values for ^{60}Co in Table 4 derived from Surgeonfish and Goatfish from islands at Enewetak. Analyses of the reef fish data from B-1 sampled prior to 1978 gave an effective half life for ^{60}Co of 3.0 ± 0.5 y. This value is in good agreement with the value of

3.0 ± 0.4 y determined from the viscera samples by Schell (1987). However, a much different effective half life results when the entire data set of 53 measurements from 1964 to 1994 from the entire lagoon is used to generate the decay constant. The computed effective half-life of 5.3 ± 0.5 y from this analysis is no different than the radiological half life. Over the long term the loss of ^{60}Co from Bikini lagoon occurs principally by radioactive decay or the rate of release from the environmental components diminished after 1978. At Enewetak the effective half life from the analysis of 58 data points using a regression analysis is 4.0 ± 0.6 y. This half life is similar in value to one determined by Nelson and Noshkin (1973) comparing viscera data from fish caught in 1964 and 1972, but on the other hand it cannot be argued to be significantly different from the value of the radiological half-life (5.26 y). There may be a somewhat faster rate of depletion at Enewetak, but the true value is again masked by the errors generated from the analysis. At best, the effective half life from the majority of results indicates a value of 4 to 5.2 y at both atolls.

The behavior of ^{207}Bi is different at the 2 Atolls. In 26 samples of goatfish from Enewetak lagoon the best fit to all data yielded an effective half-life of 5.1 ± 0.9 y. This value is in agreement with the Nelson and Noshkin (1973) result of 5.0 ± 3.0. This removal half-time from all goatfish results is clearly faster than the radiological half-life of 32.2 y. At Bikini there was substantially less usable data. However, the LSF for the 11 samples generated an effective half-life of 30 ± 12 y, which is equivalent to the radiological half-life. Too little data were available at B-1 prior to 1978 to compare with the Schell (1987) viscera result. Because of the large error associated with the effective half-life, any definitive conclusions regarding ^{207}Bi at Bikini are not clear cut. It suggests that any significant loss of ^{207}Bi from the lagoon environment is probably only by radioactive decay. If true, the radionuclide must be in a chemical or physical form very different from that associated with sediments source terms in Enewetak lagoon.

CONCLUSIONS

A variety of different radionuclides was found accumulated in all species of fish from Bikini and Enewetak lagoons. Over the years many of the radionuclides have diminished by radioactive decay and by natural processes. Fish collected in the 1980's and 1990's show only low concentrations of a few remaining long-lived radionuclides in flesh and other tissues. The data generated from the marine studies show that the radiological dose from manmade radionuclides in the marine food chain contribute less than 0.1% of the total 30-y integral dose equivalent at both Atolls (Robison 1973; Robison et al. 1987; Robison et al. 1997). The ingestion dose was derived principally from 3 gamma-emitting radionuclides, ^{137}Cs, ^{60}Co and ^{207}Bi; the transuranic radionuclides $^{238,239+240}$Pu and ^{241}Am; and ^{90}Sr. The largest contributor to the total marine dose was from ^{137}Cs accumulated in the edible flesh. The transuranic radionuclides and ^{90}Sr contributed little to the total dose from ingestion of marine foods. Our collection program was phased out in 1985, but fish samples were again collected in the 1990's to verify the results of the original assessment and to determine what, if any, changes occurred in the concentrations of gamma emitting radionuclides in edible muscle tissue. Resources only permitted analysis of muscle tissue in these samples after dissections. Of the gamma emitting radionuclides generated by the nuclear tests, only ^{60}Co, ^{137}Cs and ^{207}Bi remain above detection limits by gamma spectrometry in flesh of some but not all fish.

These new data and the results from our earlier studies and work by others provide a large, valuable and unique data base for radionuclides in the flesh of different fish that span 31 y, from 1964 to 1995. Some reef fish can be used as indicator species because their body burden is derived from feeding, over a lifetime, within a relatively small area containing the contamination. The change in body concentration over time is related to the local diagenic processes that are responsible for the release and recycling of the radionuclides. The change in concentrations observed in several non-migratory reef species is used to describe the effective half lives for ^{60}Co, ^{137}Cs, and ^{207}Bi in the lagoon environments during the 31-y period between 1964 and 1995. This half life consists of a physical decay term and a recycling or environmental decay term. This latter term is related to the processes which control the removal and transport of a radionuclide from the environment. Sufficient measurements for ^{137}Cs, ^{60}Co and ^{207}Bi were available for some reef species of fish repeatedly sampled from specific locations at Bikini and Enewetak to determine an effective environmental decay constant from a least square analysis (LSF) of the data.

The results of the analysis indicate the removal rates for the 3 radionuclides are significantly different. ^{137}Cs is removed from the marine environments of Bikini and Enewetak with an effective half life of 9–12 y that is significantly less than the radiological half life. The natural processes acting on ^{137}Cs in the environment will reduce any radiological exposure from ingestion of marine foods. Every 9–12 y the inventory of ^{137}Cs in the sedimentary reservoirs is reduced in half and radiological decay accounts for about 21% of the loss. The remaining 29% was remobilized from the environment to the water column in a dissolved state over the 9–12-y period. Within the lagoon, excess dissolved ^{137}Cs has been measured in water samples taken on our sampling programs from all areas of both atolls for many years (see, for example, Noshkin and Robison 1997; this volume). The lagoon water mass containing the ^{137}Cs is continuously transported over the reef or through the passes and eventually exits the atoll and mixes with the north equatorial Pacific water mass.

Some slight difference could be assigned to the estimated effective half-life for ^{60}Co at Enewetak and Bikini. However, it would appear that most of the radionuclide is lost from both environments by radioactive decay. Little enters the water column from the sediments as a dissolved species. Most ^{60}Co accumulated by fishes must be derived from food and sedimentary particles passing through the gut rather than direct uptake from water.

The results from the analysis of the ^{207}Bi in the indicator fish species suggest a difference in behavior at the two Atolls. At Enewetak the radionuclide is lost from the environment with an effective half life of 5.1 y. The radionuclide is mobilized from the sedimentary reservoir at a rate similar to ^{137}Cs and is then diluted with ocean water and is eventually transported from the Atoll. On the other hand, only radioactive decay may account for the rate at which the radionuclide is disappearing from Bikini lagoon. Again most body burdens of ^{207}Bi in fish from Bikini must be derived from material passing through the gut rather than from the water. The different behavior of ^{207}Bi at the Atolls must be controlled by different chemical-physical properties of the contaminated particles retaining the radionuclide.

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APPENDIX A

Table A1. Concentration of ^{137}Cs, ^{60}Co, and ^{207}Bi in flesh (muscle) of fish caught between 1964 and 1995 from islands of Enewetak Atoll.

Sample ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			E-							
(1)[c]	Butterflyfish	Aug-64	2	3	13.9		105.9			
(1)	Damselfish	Aug-64	2	10	15.5		70.1			
9109	Goatfish	Nov-78	2	22	1.5	4	6.4	2	12.3	2
g509	Goatfish	Aug-83	2	26	2.0	6	4.0	3	26.5	2
(1)	Grouper	Aug-64	2	1	11.4		11.4		15.5	
(1)	Grouper	Aug-64	2	1	8.1		32.6		17.9	
(2)[d]	Mullet-C	Nov-72	2	1	5.1	14	30.1	5	1.1	38
2610	Mullet-C	Apr-76	2	4	7.8	2	8.9	2	0.4	7
g586	Mullet-C	Aug-83	2	9	3.0	6	4.8	4	0.1	>100
g552	Mullet-C	Aug-83	2	6	5.9	2	4.0	3	0.2	26
9103	Mullet-N	Nov-78	2	17	2.5	4	9.0	2	0.2	18
(1)	Snapper	Aug-64	2	1	27.7		51.3		26.9	
(1)	Squirrelfish	Aug-64	2	3	9.0		23.6		6.9	
(1)	Surgeonfish	Aug-64	2	1	18.7		43.2			
5286	Surgeonfish	May-76	2	52	8.1	2	6.4	2	0.4	11
9115	Surgeonfish	Nov-78	2	22	6.7	3	3.0	6	0.1	>100
g529	Surgeonfish	Aug-83	2	16	9.6	2	1.1	7	0.1	30
(1)	Triggerfish	Aug-64	2	3			203.7		21.2	
g822	Ulua	Aug-83	2	1	6.2	4	2.1	7	11.4	2
(1)	Wrasse	Aug-64	2	6			75.0			
(1)	Grouper	Aug-64	5	9	4.7		30.1		8.1	
(1)	Grouper	Aug-64	5	2			21.2		36.7	
(1)	Mullet-N	Aug-64	5	2			171.1			
(1)	Parrotfish	Aug-64	5	2	17.9		6.3			
(1)	Surgeonfish	Aug-64	5	3			37.5			
(1)	Surgeonfish	Aug-64	5	5	130.4		211.9			
(1)	Triggerfish	Aug-64	5	1			75.0			
msa394	Goatfish	Jul-81	9	34	1.7	5	10.3	2	49.0	1
(2)	Mullet	Nov-72	9	1	35.0	5	163.0	3	1.6	45
5302	Mullet-C	Mar-78	9	16	7.8	2	1.3	5	0.1	>100
msa677	Mullet-C	Jul-81	9	62	3.1	7	27.2	1	0.1	>100
(2)	Snapper	Nov-72	9	4	17.1	8	89.6	4	1	>100
msa548	Surgeonfish	Jul-81	9	52	15.3	2	2.4	5	0.1	>100
j286	Bonito	Sep-84	10	1	6.8	4	9.9	3	4.5	5
z417	Flagtail	Feb-94	10	1	1.8	44	2	>100	1	>100
7385	Goatfish	Nov-78	10	26	1.4	11	13.2	2	241.9	2
g637	Goatfish	Aug-83	10	27	1.9	13	14.0	2	524.5	2
j424	Goatfish	Sep-84	10	18	0.8	13	4.5	3	75.0	1
j428	Goatfish	Sep-84	10	17	1.1	30	8.0	4	437.2	2
z420	Goatfish	Nov-93	10	3	0.3	>100	1	>100	8.2	4
z409	Goatfish	Feb-94	10	5	1.5	21	1.7	15	109.9	6
z838	Goatfish	Feb-94	10	16	0.2	>100	1.8	29	495.4	1
z861	Goatfish	Nov-94	10	7	0.9	>100	1	>100	29.2	1
z846	Goatfish	May-95	10	8	1	>100	2	>100	5.6	8
(1)	Grouper	Aug-64	10	5	7.2					
(1)	Grouper	Aug-64	10	1	29.3					
g809	Grouper	Aug-83	10	10	2.1	5	0.8	11	15.2	1
(1)	Jack	Aug-64	10	1	10.6		57.0		48.9	
(1)	Mullet-C	Aug-64	10	5	25.3		464.4			
(2)	Mullet-C	Nov-72	10	2	1.1	23	3.6	91	0.4	60
g621	Mullet-C	Aug-83	10	15	1.5	4	1.0	5	0.0	>100
2633	Mullet-N	Apr-76	10	19	0.9	6	2.4	3	0.2	14

Sample ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			E-							
9266	Mullet-N	Jan-77	10	30	0.5	6	4.0	1	0.5	3
g627	Mullet-N	Aug-83	10	34	0.3	18	0.3	15	0.0	>100
z410	Papio	Feb-94	10	3	0.9	>100	1	>100	9.0	3
(1)	Parrotfish	Aug-64	10	1	97.8		13.0		10.6	
(2)	Parrotfish	Nov-72	10	1	8.0	9	2	>100	0.6	>100
5312	Parrotfish	Nov-78	10	1	6.9	3	0	>100	0.1	>100
msa144	Snapper	Sep-80	10	1	1.9	15	6.3	8	31.2	1
g813	Snapper	Aug-83	10	4	1.1	17	1.5	11	12.0	2
g815	Snapper	Aug-83	10	4	2.5	6	4.0	3	38.7	1
(1)	Surgeonfish	Aug-64	10	1	12.2		5.8			
(1)	Surgeonfish	Aug-64	10	5	20.4					
7377	Surgeonfish	Nov-78	10	54	5.1	2	0.4	8	0.1	>100
g632	Surgeonfish	Aug-83	10	31	5.0	3	0	>100	0.1	>100
z421	Surgeonfish	Nov-93	10	11	2.1	28	2	>100	1	>100
z411	Surgeonfish	Feb-94	10	10	4.3	9	1	>100	0.6	>100
z837	Surgeonfish	Feb-94	10	12	1.2	63	1	>100	1	>100
z865	Surgeonfish	Nov-94	10	58	2.2	28	2	>100	1	>100
z863	Surgeonfish	May-95	10	24	2.8	13	1	>100	0.5	>100
(1)	Triggerfish	Aug-64	10	2			31.0			
g811	Triggerfish	Aug-83	10	1	0.5	30	9.0	2	12.5	2
j289	Ulua	Sep-84	10	2	7.0	2	0.8	6	3.5	2
msa138	Bonito	Sep-80	19	1	2.3	7	5.1	3	6.9	3
msa98	Mullet-C	Sep-80	19	5	0.8	20	1.5	21	0.1	>100
msa92	Mullet-C	Sep-80	19	35	3.5	4	3.2	4	0.1	>100
2641	Mullet-N	Apr-76	19	29	0.4	8	1.3	4		
9260	Mullet-N	Jun-77	19	58	0.3	5	1.0	3	0.2	6
5270	Surgeonfish	May-76	19	28 ocean	4.0	20	0.8	8	0.0	>100
5278	Surgeonfish	May-76	19	40 ocean	2.3	4	0.9	9	0.0	>100
7275	Surgeonfish	Nov-78	19	46	9.2	1	1.0	8	0.0	>100
z077	Surgeonfish	Nov-93	19	11	1.0	40	1	>100	0.9	>100
z078	Goatfish	Nov-93	20	7	2	>100	2	>100	4	>100
(2)	Mullet	Nov-72	20	1	1	>100	1.5	0	0.7	>100
(2)	Parrotfish	Nov-72	20	1	3.4	17	2	>100	0.2	>100
(2)	Snapper	Nov-72	20	2	2.6	28	2	>100	0.7	>100
(2)	Snapper	Nov-72	20	1	1.1	21	0	>100	1.0	25
(2)	Snapper	Nov-72	20	4	1	>100	1	>100	1	>100
(2)	Ulua	Nov-72	20	1	2.0	21	0	>100	2.0	26
g820	Barracuda	Aug-83	24	1	1.6	13	0.8	14	7.1	2
z852	Flagtail	Nov-94	24	9	1.1	31	1	>100	0.8	>100
(1)	Goatfish	Aug-64	24	5			264.1		102.2	
msa24	Goatfish	Sep-80	24	42	0.6	4	0.3	1	12.6	2
msa30	Goatfish	Sep-80	24	42	1.4	2	5.7	1	25.0	1
msa692	Goatfish	Jul-81	24	34	2.0	7	22.6	2	19.9	8
z088	Goatfish	Nov-93	24	16	1	>100			14.4	2
z834	Goatfish	Nov-93	24	15	0.5	63	6.0	10	9.1	3
z848	Goatfish	Nov-94	24	29	1	>100	2.4	21	6.6	7
z850	Goatfish	May-95	24	57	1	>100	1.2	32	3.7	9
z867	Goatfish	May-95	24	18	0	>100	2	>100	3.6	11
(2)	Grouper	Nov-72	24	1	2.8	27	6.3	16	21.3	4
(1)	Halfbeak	Aug-64	24	10			67.3			
9165	Mullet-C	Nov-78	24	22	1.0	2	5.5	2	0.0	32
msa44	Mullet-C	Sep-80	24	14	1.1	3	1.5	2	0.0	27
msa36	Mullet-C	Sep-80	24	30	0.3	5	0.8	5	0.0	34
g647	Mullet-C	Aug-83	24	33	1.1	5	0.9	6	0.0	>100
z862	Mullet-C	May-95	24	6	0.0	>100	1	>100	0.6	>100
2618	Mullet-N	Apr-76	24	22	0.8	2	6.6	2	0.5	11
msa66	Mullet-N	Sep-80	24	29	0.6	4	0.7	23	0.0	80
msa74	Mullet-N	Sep-80	24	29	0.3	8	0.7	6	0.0	25
msa467	Mullet-N	Jul-81	24	21	0.5	12	2.3	3	0.0	>100
msa834	Mullet-N	Jun-82	24	16	0.7	20	2.2	7	0.1	>100
g642	Mullet-N	Aug-83	24	5	0.7	18	1.5	10	0.1	>100
z414	Mullet-N	Feb-94	24	5	1.4	64	1.7	23	1	>100
z836	Mullet-N	Feb-94	24	17	1.6	49			2	>100
z866	Mullet-N	May-95	24	55	1	>100	2	>100	1	>100
msa62	Parrotfish	Nov-72	24	2	4.2	61	1	>100	0.5	>100
(2)	Parrotfish	Sep-80	24	2	2.6	3	0.6	5	0.1	24
z857	Parrotfish	Nov-94	24	6	5.6	4	1	>100	0.4	>100
msa82	Snapper	Sep-80	24	1	1.8	3	10.3	2	9.7	2

Sample ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			E-							
msa88	Snapper	Sep-80	24	1	4.9	1	3.7	1	7.1	2
g807	Snapper	Aug-83	24	1	1.8	5	2.6	3	6.7	1
(1)	Surgeonfish	Aug-64	24	10	52.0		23.0			
5294	Surgeonfish	May-76	24	28 ocean	1.6	5	2.2	6	0.0	>100
7377	Surgeonfish	Nov-78	24	10	5.1	2	0.4	8	0.0	>100
9171	Surgeonfish	Nov-78	24	51	14.4	2	2.3	3	0.0	>100
msa58	Surgeonfish	Sep-80	24	28 south	1.7	2	0.3	8	0.0	35
msa52	Surgeonfish	Sep-80	24	74	7.9	2	0.6	8	0.1	29
msa686	Surgeonfish	Jul-81	24	50	9.7	2	1.0	10	0.1	>100
msa828	Surgeonfish	Jun-82	24	57	9.1	2	0.6	17	0.1	>100
g652	Surgeonfish	Aug-83	24	27	5.4	3	0.7	27	0.1	>100
z091	Surgeonfish	Nov-93	24	5	8.1	14	3	>100	2	>100
z412	Surgeonfish	Feb-94	24	8	4.7	11	1	>100	0.6	>100
z835	Surgeonfish	Feb-94	24	42	4.5	6	1	>100	0.5	>100
z849	Surgeonfish	Nov-94	24	62	1.7	33	1	>100	1	>100
z851	Surgeonfish	Nov-94	24	60			2	>100	1	>100
z843	Surgeonfish	May-95	24	46	1.8	35	2	>100	1	>100
z844	Surgeonfish	May-95	24	9	1.9	11	1	>100	0.4	>100
z845	Surgeonfish	May-95	24	5	1	>100	1.8	26	0.9	>100
(2)	Tuna	Nov-72	24	1	3.7	11	9.4	10	9.4	10
(2)	Tuna	Nov-72	24	1	2.4	21	6.8	10	7.4	9
(2)	Tuna	Nov-72	24	1	1.3	33	3.2	14	2.0	17
(2)	Ulua	Nov-72	24	2	3.9	22	11.1	9	2.8	33
9254	Goatfish	Apr-76	33	58	0.3	16	6.9	2	29.3	1
2602	Mullet-C	Apr-76	33	6	0.5	13	0.9	11	0.1	13
(2)	Parrotfish	Nov-72	33	2	0.6	83	0.4	>100	0.3	>100
5232	Surgeonfish	May-76	33	52	0.8	13	0.4	35	0.0	>100
(2)	Snapper	Nov-72	35	1	1.1	38	3.1	14	2.9	12
(2)	Ulua	Nov-72	35	1	4.6	15	10.2	10	7.8	7
(2)	Grouper	Nov-72	37	1	4.5	13	1	>100	17.8	5
(2)	Grouper	Nov-72	37	1	4.3	18	3.7	26	5.4	11
2625	Mullet-C	Apr-76	37	8	0.2	28	0.4	11	0.1	23
(2)	Parrotfish	Nov-72	37	1	15.0	6	2	>100	0.6	>100
(2)	Snapper	Nov-72	37	1	0.9	>100	1	>100	0.6	>100
5239	Surgeonfish	May-76	37	37	0.5	9	0.1	32	0.1	>100
7176	Surgeonfish	Nov-78	37	8	1.8	11	0	>100	0.1	>100
(2)	Ulua	Nov-72	37	1	3.1	28	18.7	9	48.0	3
(1)	Grouper	Aug-64	38	10			6.3		5.8	
(1)	Grouper	Aug-64	38	1			6.6		12.8	
j736	Mullet-C	Sep-84	38	8	0.2	11	1.1	3	0.0	>100
(2)	Snapper	Nov-72	38	1	2.6	33	5.6	16	16.2	5
(1)	Surgeonfish	Aug-64	38	10			11.9			
5247	Surgeonfish	May-76	38	40	1.0	7	1.8	5	0.4	8
(2)	Parrotfish	Nov-72	39	1	0.3	25	2	>100	0.9	>100
(1)	Goatfish	Aug-64	43	5			68.9		64.6	
(1)	Grouper	Aug-64	43	1	85.0		15.3		12.8	
(1)	Grouper	Aug-64	43	1			20.4		54.4	
(1)	Jack	Aug-64	43	1	10.2		59.5		7.0	
(2)	Mullet-C	Nov-72	43	2	1.0	17	9.4	18	0.5	>100
2594	Mullet-C	Apr-76	43	11	2.8	4	9.0	4	0.9	3
(2)	Parrotfish	Nov-72	43	1	2.4	18	1	>100	0.3	>100
msa132	Barracuda	Sep-80	45	1	2.1	11	1.8	12	12.5	3
msa158	Mackerel	Sep-80	45	1	2.4	9	4.3	6	1.8	10
g497	Mackerel	Aug-83	45	7	1.7	5	1.9	4	1.2	5
j283	Mackerel	Sep-84	45	2	1.5	17	0	>100	0.1	>100
msa126	Ulua	Sep-80	45	1	8.2	1	3.7	2	5.8	10
g503	Ulua	Aug-83	45	3	2.9	3	1.4	5	1.3	4
j290	Ulua	Sep-84	45	2	2.1	8	1.1	10	3.0	4

[a] Sample ID used at Lawrence Livermore National Lab.
[b] No error was given for the 1964 data set. Elsewhere the 1 σ counting error is expressed as the percent of the value listed.
[c] (1) data from Welander et al. (1967).
[d] (2) data from Nelson and Noshkin (1973).
Notes:
2,579 total fish processed for 178 samples between 1964 and 1995. All results reported on date of collection.
163 measurements for ^{137}Cs; 90% reported above detection limits.
173 measurements for ^{60}Co; 76% reported above detection limits.
159 measurements for ^{207}Bi; 57% reported above detection limits.

APPENDIX B

Table 2A. Concentration of ^{137}Cs, ^{60}Co and ^{207}Bi in flesh (muscle) of fish caught between 1964 and 1994 from islands of Bikini Atoll.

ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			B-							
(2)[d]	Goatfish	May-70	1	14	6.8	33	101.4	3	62.9	3
9121	Goatfish	Nov-78	1	33	5.5	3	21.2	1	50.4	2
g576	Goatfish	Aug-83	1	11	6.0	6	6.7	4	36.0	4
z423	Goatfish	Dec-92	1	5	2.2	35	6.1	10	37.2	2
(4)	Mullet-C	Jul-76	1	6	5.6	15	12.3	7		
2896	Mullet-C	Jan-77	1	8	9.7	3	11.2	2	0.0	100
9133	Mullet-C	Nov-78	1	12	14.7	1	33.2	1	0.1	21
a356	Mullet-C	Feb-81	1	14	8.4	3	8.2	3	0.0	100
g561	Mullet-C	Aug-83	1	11	4.4	2	2.5	26		
z415	Mullet-C	Dec-92	1	1	1.7	58	3	100	2	100
z859	Mullet-C	Nov-94	1	8	2.4	28	2	100	10.4	
(1)[c]	Mullet-N	Aug-64	1	10	52.1		798.5			
(4)	Mullet-N	Jul-76	1	6	5.1	13	15.7	6		
a458	Mullet-N	Jan-77	1	14	8.6	3	18.8	3	0.0	100
(4)	Mullet-N	Oct-77	1	10	6.5	13	13.1	7		
9127	Mullet-N	Nov-78	1	18	7.3	2	15.9	1	0.0	100
z422	Mullet-N	Dec-92	1	4	2.7	34	6.5	13	1	100
z853	Mullet-N	Nov-94	1	39	1	100	0.8	100	0.6	100
(3)[e]	Snapper	May-72	1	6	7.9	8	25.6	3	36.8	2
(4)[f]	Snapper	Jul-76	1	4	4.4	15	8.0	10	8.8	10
(1)	Surgeon	Aug-64	1	7	171.1		67.6			
9159	Surgeon	Nov-78	1	4	4.9	1	8.6	1	0.1	100
g515	Surgeon	Aug-83	1	36	17.1	1	1.2	6	0.1	31
g521	Surgeon	Aug-83	1	37	15.0	1	1.6	7	0.1	100
z419	Surgeon	Dec-92	1	11	8.2	6	1.9	20	0.6	100
(1)	Trigger	Aug-64	1	1	97.8		260.7			
(4)	Ulua	Nov-72	1	1	10.6	8	5.8	10	4.1	11
(4)	Goatfish	Nov-72	S of B-1	1	11.2	17	112.4	2	11.2	8
(4)	Goatfish	Nov-72	S of B-1	10	1.5	24	12.8	7	2.3	11
(4)	Mullet-N	Nov-72	S of B-1	13	5.8	16	81.9	2		
2880	Mullet-C	Jan-77	2	21	14.1	2	10.1	1	0.0	100
(1)	Butterfly	Aug-64	3	1			114.1			
(1)	Grouper	Aug-64	3	5			12.2			
(1)	Jack	Aug-64	3	1			32.6			
(1)	Surgeon	Aug-64	3	4	24.4		26.9			
(1)	Triggerfish	Aug-64	3	1			97.8			
(1)	Wrasse	Aug-64	3	1			37.5			
(4)	Goatfish	Nov-72	5	3	5.0	16	40.0	2	43.5	2
7251	Goatfish	Nov-78	5	22	1.9	4	13.8	2	3.3	8
a233	Goatfish	Feb-81	5	44	3.1	5	16.0	2	2.1	4
z413	Goatfish	Dec-92	5	6	0.5	100	6.4	11	10.1	7
z868	Goatfish	Nov-94	5	33	1.3	19	0.7	100	0.5	100
7245	Mullet-C	Nov-78	5	8	13.8	1	9.0	1	0.0	100
a186	Mullet-C	Feb-81	5	7	12.6	2	6.4	2	0.1	100
(4)	Mullet-N	Nov-72	5	14	3.7	14	17.2	5		
7224	Mullet-N	Nov-78	5	24	2.2	3	9.0	1	0.0	100
g372	Mullet-N	Jun-82	5	33	2.5	3	4.9	2	0.0	100
z418	Mullet-N	Dec-92	5	4	0.9	100	0.8	64	0.7	100
(4)	Parrotfish	Nov-72	5	1	3.5	18				
a240	Parrotfish	Feb-81	5	3	8.6	4	1.5	14	0.2	100
z869	Parrotfish	Nov-94	5	6	0.3	100	1	100	0.9	100
z860	Perch	Nov-94	5	7	0.6	90	2	100	0.9	100
(4)	Queenfish	Nov-72	5	1	29.1	3	23.8	4	6.7	8
(4)	Surgeon	Nov-72	5	17	17.1	5	5.0	7		
7257	Surgeon	Nov-78	5	20	8.4	1	2.0	5	0.0	100
a224	Surgeon	Feb-81	5	33	11.8	3	3.8	7	0.2	100
z416	Surgeon	Dec-92	5	12	4.4	12	2.0	22	0.6	100
7370	Goatfish	Nov-78	6	39	0.8	6	2.4	3	0.7	4
a841	Goatfish	Sep-80	6	39	0.5	14	1.2	8	0.7	7
j420	Goatfish	Sep-84	6	58	0.7	16	1.3	10	1.6	6
j422	Goatfish	Sep-84	6	26	0.4	24	1.1	14	1.2	7
z81	Goatfish	Dec-92	6	9	0.5	100	2	100	1	100
z855	Goatfish	Nov-94	6	8	1	100	0.7	100	0.5	100

ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			B-							
a372	Mullet-C	Sep-80	6	14	1.9	3	6.5	1	0.0	100
a848	Mullet-C	Sep-80	6	7	3.9	4	8.3	3	0.0	100
a253	Mullet-C	Feb-81	6	8	2.2	4	4.8	2	0.0	100
j734	Mullet-C	Sep-84	6	12	2.0	2	3.4	1	0.0	100
z82	Mullet-C	Dec-92	6	2	1.8	20	0.9	45	0.9	100
a401	Mullet-N	Feb-81	6	38	1.1	10	3.3	8	0.1	100
g363	Mullet-N	Mar-82	6	31	0.8	8	1.9	6	0.0	100
(4)	Parrotfish	Oct-72	6	1	8.6	10	2.2	26		
(1)	Snapper	Aug-64	6	1	19.6		61.1		26.1	
(1)	Snapper	Aug-64	6	1	6.7		5.6			
(4)	Surgeon	Nov-72	6	3	3.6	7	1.3	19		
7352	Surgeon	Nov-78	6	55	6.2	2	0.7	7	0.0	100
z83	Surgeon	Dec-92	6	7	2.9	22	2	100	1.0	100
z864	Surgeon	Nov-94	6	53	1.8	21	2.8	15	0.6	100
(4)	Mullet-N	Nov-72	B-6 ocean	14	2.0	19	11.3	3		
(4)	Parrotfish	Nov-72	B-6 ocean	3	4.5	15	0.7	72		
(4)	Snapper	Dec-74	9	1	0.9	60	2.2	42		
7263	Goatfish	Nov-78	10	42	0.5	6	1.5	3	0.8	3
2888	Mullet-N	Jan-77	10	43	0.6	10	7.8	2	0.1	30
7269	Surgeon	Nov-78	10	46	1.7	4	1.0	14	0.0	100
(4)	Goatfish	Nov-72	12	10	0.7	33	7.1	4	1.8	14
7200	Goatfish	Nov-78	12	42	0.7	6	3.5	2	1.6	2
j415	Goatfish	Sep-84	12	13	0.7	18	0.9	18	1.8	7
(1)	Grouper	Aug-64	12	5	8.1					
(5)	Grouper	Apr-75	12	1	3.9	23	1.4	63		
2860	Mullet-C	Jan-77	12	11	1.0	6	2.8	6	0.0	100
(1)	Mullet-N	Aug-64	12	3			26.9			
7194	Mullet-N	Nov-78	12	21	0.3	11	3.7	2	0.0	100
(4)	Parrotfish	Nov-72	12	3	4.0	6	0.4	60		
(5)	Parrotfish	Apr-75	12	1	3.3	19				
(4)	Rudderfish	Nov-72	12	1			1.2	36		
(1)	Surgeon	Aug-64	12	3	14.7		7.7			
(1)	Surgeon	Aug-64	12	5	6.9		5.5			
(4)	Surgeon	Nov-72	12	6	2.5	13	0.6	57		
7188	Surgeon	Nov-78	12	64	2.3	2	0.8	6	0.0	100
2851	Mullet-C	Jan-77	13	22	0.8	5	2.4	5	0.0	100
a530	Mullet-N	Feb-81	13	23	0.4	14	1.7	8	0.0	100
(4)	Goatfish	Oct-77	15	7	7.2	14	16.3	10	52.1	5
(1)	Ladyfish	Aug-64	15	2			42.4		57.9	
7281	Goatfish	Nov-78	17	37	1.8	4	9.8	2	8.4	2
7293	Mullet-C	Nov-78	17	9	3.3	2	5.3	2	0.0	100
j730	Mullet-C	Sep-84	17	31	0.5	13	1.4	7	0.0	100
(4)	Mullet-N	Nov-72	17	14	1.6	18	12.3	2		
2872	Mullet-N	Jan-77	17	58	1.5	4	14.0	1	0.2	13
7299	Mullet-N	Nov-78	17	18	0.4	100[b]	46.1	2	0.4	100
(4)	Parrotfish	Nov-72	17	6	4.2	5	2.3	10		
7287	Parrotfish	Nov-78	17	5	5.2	2	0.7	9	0.0	100
(4)	Surgeon	Nov-72	17	13	8.3	4	5.6	6		
g621	Surgeon	Aug-83	17	70	1.6	5	0.2	25		
(4)	Ulua	Nov-72	17	1	7.9	5	4.1	10	0.7	43
(4)	Ulua	Nov-72	17	1	2.5	10	5.5	6	0.3	100
a967	Ulua	Jun-82	22	1	14.0	4	1.8	4	4.1	10
g421	Ulua	Jun-82	22	2	13.4	2	2.0	5	1.4	5
7311	Goatfish	Nov-78	23	47	1.8	6	14.3	1	22.2	1
(1)	Grouper	Aug-64	23	1			30.1		10.6	
(4)	Mullet-N	Nov-72	23	8	0.5	80	27.6	3		
7305	Mullet-N	Nov-78	23	35	0.8	7	15.2	1	0.2	20
(1)	Snapper	Aug-64	23	1			74.1		13.9	
(1)	Snapper	Aug-64	23	1			89.6		10.6	
(1)	Snapper	Aug-64	23	1			21.2		5.8	
(1)	Snapper	Aug-64	23	1			130.4		18.7	
7346	Snapper	Nov-78	23	1	5.4	3	7.6	2	12.2	2
(1)	Surgeon	Aug-64	23	1			97.8			
(4)	Surgeon	Nov-72	23	3	4.7	16	7.9	10		
(1)	Trigger	Aug-64	23	2			244.4			
(2)	Tuna	May-72	lagoon	1	26.3	3	13.6	7	77.1	1
(3)	Tuna	May-72	lagoon	1	7.5	5	3.3	12	0.7	43

ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			B-							
(4)	Rainbow	Oct-72	lagoon	1	1.5	63				
(4)	Rainbow	Nov-72	lagoon	1	9.9	9	37.8	2	3.7	10
(4)	Bonito	Nov-72	lagoon	1	4.9	8	9.0	5	0.7	43
(5)[g]	Mackerel	Dec-74	lagoon	1	6.9	6	17.7	6		
(5)	Snapper	Dec-74	lagoon	1			0.8	50		
(4)	Snapper	Jul-76	lagoon	1	10.1	8	5.9	13	16.8	5
(4)	Snapper	Jul-76	lagoon	1	21.1	8	9.7	17	34.9	5
(4)	Snapper	Jul-76	lagoon	1	41.5	7	13.3	11	25.9	6
(4)	Snapper	Jul-76	lagoon	1	50.1	5	18.2	8	31.9	5
(4)	Snapper	Jul-76	lagoon	1	28.4	8	15.4	16	15.4	8
(4)	Snapper	Oct-77	lagoon	1	40.4	6	9.5	18	30.1	5
(4)	Barracuda	Oct-77	lagoon	4	6.4	11	3.1	16	5.3	8
(4)	Barracuda	Oct-77	lagoon	1	18.5	9	5.6	16	26.9	5
(4)	Bonito	Oct-77	lagoon	1	5.7	19	2.9	30	1.6	33
(4)	Mackerel	Oct-77	lagoon	1	2.1	46	4.1	28		
(4)	Ulua	Oct-77	lagoon	1					6.5	16
7322	Jack	Nov-78	lagoon	1	9.5	2	12.0	2	4.5	2
7334	Mackerel	Nov-78	lagoon	1	2.9	3	2.0	5	0.1	25
7328	Snapper	Nov-78	lagoon	2	0.4	17	0.2	65	6.2	2
7340	Snapper	Nov-78	lagoon	1	1.8	4	3.1	4	0.4	10
a247	Mackerel	Feb-81	lagoon	1	3.7	5	2.4	7	0.3	32
j293	Bonito	Sep-84	lagoon	1	6.5	3	7.4	3	6.6	3
j291	Rainbow	Sep-84	lagoon	1	2.3	8	1.6	11	0.2	100
j292	Snapper	Sep-84	lagoon	1	6.4	3	1.6	8	1.2	8
j294	Ulua	Sep-84	lagoon	1	7.1	2	3.6	2	4.1	2

[a] Sample ID used at Lawrence Livermore National Lab.
[b] No error was given for the 1964 data set. Elsewhere the 1 σ counting error is expressed as the percent of the value listed.
[c] (1) data from Welander et al. 1967.
[d] (2) data from Held 1971.
[e] (3) data from Lynch, et al. 1975.
[f] (4) data from Schell et al. 1978.
[g] (5) data from Nelson 1977.
Note: 1,890 total fish processed for 155 samples between 1964 and 1994. All results reported on date of collection.
138 measurements for 137Cs; 95% reported above detection.
150 measurements for Co; 94% reported above detection.
111 measurements for 207Bi; 58% reported above detection.